

THE PROGRESSIVE SYNTHESIS OF ARCHITECTURE AND ENGINEERING IN MODERN BRIDGE DESIGN

by

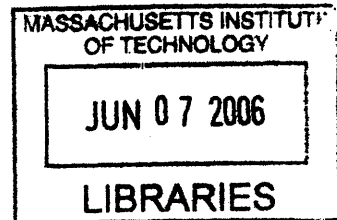
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Bachelors of Architecture
Virginia Polytechnic Institute & State University, 2005

Submitted to the Department of
Civil and Environmental Engineering in
Partial Fulfillment of the Requirements for the Degree of

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History states that architects and engineers rarely operate in a peaceful environment as each have their own specific agendas to fulfill. The architect appeals to the plastic form of a building before tending to its structural behavior while the engineer tends towards the opposite. While both are striving for a workable structure, their priorities are mismatched.

Bridge building, through history usually was considered an engineering feat as it was strictly constructed to traverse a crevasse, waterway or some other obstacle. However through the 20th century, the respective roles have evolved and bridges have become more than a mere span. The architect has revolutionized the art of building a bridge, but was it the technology of the engineer that helped propel the architect or was it just a simple awakening by the architectural community?

By analyzing a variety of bridges by Santiago Calatrava and Robert Maillart among other architects and engineers that have been the most influential in this movement, and their construction process, form, materials, and design process, et al, it can be observed how the bridge building process has evolved. Bridge building is an engineering movement no more, but it is not an architectural movement either. In part, by way of these bridge building pioneers, the two professions have started to sideline their angst and ridicule and create a new harmony throughout the built environment.

Thesis Supervisor: Jerome Connor

Title: Professor of Civil and Environmental Engineering

ACKNOWLEDGMENTS

My studies as an architect led me down this path; to see the built environment as an engineer. I would be inundated with a flurry of strange equations, variables, mathematics, and alphabets. As an engineer, I would have to make sense of these concepts and apply them to my work.

The following document contains no such items.

Considering that, it is almost unheard of not to have at least one equation in an engineering thesis, so I've decided to include the most important equation I've learned in the past 23.715 years of my life:

$$\textbf{SUPPORT + LOVE + KNOWLEDGE = "my success"} \quad (1)$$

I would like to take this chance to mention all the variables in this equation:

*S*antiago Calatrava – the man, the myth, the legend...

*U*ncanny architects – the Stoekelites who survived, among others...

*P*arents – Lois & Brian...Mom & Dad, where would I be without you?...

*P*rofessors – Mario, Gene, Mehdi, Paul...

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*R*esidents of Tang – Brian, Paul, Kush and the random others around the building...

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*L*auryn – My love, my life! What more could I ask for...

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*V*irginia Tech friends – Z, T, K, Blum, and too many others to list...

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*G*od – for the strength to endure life's struggles...

*E*veryone else I failed to mention in these few lines...

THANK YOU

“Too many professors equate analysis with design. Analysis is only an aid to design.”

John M. Hayes

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1 INTRODUCTION

*“The divorce of architecture and engineering is long standing and now,...
almost ubiquitous¹”*

This statement by Santiago Calatrava epitomizes the current state of the built environment. It is what every student of the trade learns in school, and whichever discipline they decide to embark upon, they are told in more ways than one that the “other” profession, whether it be architecture or engineering, is unnecessary. The engineer looks at the architect as a scatterbrained designer with erroneous and outlandish ideas, most of which are not suitable for building, or so aesthetically frivolous that the engineer can only cringe at their efforts. The architect views the engineer as an uninspired, number-crunching, efficiently skilled problem solver who does not like to take any risk, hoping for the mundane and trite buildings to pass over their desk to make their job easier. These stereotypes are so ingrained by the end of the students’ formal education that it is difficult to reverse their preconceptions. In reality, however, both professions can not stand alone for fear of treading too much on either extreme. There is a balance that must occur and in the real world, it happens, but that has not always been the case.

Bridge building, through history, usually was considered an engineering feat as bridges are constructed to traverse a crevasse, waterway or some other obstacle. However through the 20th century, the respective roles of bridges have become more than just mere spans. More particularly, the past 100 years have brought developments in materials and construction technology, thus contributing to radical transformations from

¹ Calatrava, Discussions p. 7

the “large and bulky” to the “sleek and sexy.” Robert Maillart’s genius was one of the first in the modern movement, starting around the turn of the 20th century, to optimize reinforced concrete bridge sections; while through the last 100 years, his methods are still being used. Continuing with Othmar Ammann, Christian Menn, and more recently Santiago Calatrava, these designers have taken traditional methods further and have reshaped the image of the footbridge to such that the architect is trying to eliminate the engineer, but will ultimately fail as a synthesis between the two professions must form.

It was Vitruvius that said structures/architecture must exhibit three attributes: Utilitas (appropriateness, practicality), Firmitas (stability, solidity) and Venustas (grace, beauty)² and until this time, bridgework typically lacked at least one of the three. However, it is more than just merely satisfying these categories, but rather one can establish a greater understanding of the object and its attributes. Through these designers and their techniques, bridges now can be considered more precisely structural art, combining the most important attributes from both professions of engineering and architecture.

² http://darkwing.uoregon.edu/~struct/resources/essays/influences_on_choice_1.html

2 ARCHITECTURE VS. ENGINEERING

In academia, the engineer and the architect are brought up with two distinct notions of what their roles are in the built environment. Generally, the architect is known to deal with the aesthetics or the arrangements of form on the site in order for the observer to maximize his experience and appreciate the emotions evoked. These senses are heightened as a result of the care and knowledge the architect has in acquiring a certain form that, when designed correctly, will achieve the desired function, noting that pure ornamentation is not good design. Only when both the function and the form are reconciled in one system can one consider the object “architecture.” The engineer, on the other hand, is there to make sure that the structure is able to be erected. Once a form is realized by the architect, the engineer is the one who approves the constructability of the object proposed by the architect, by mathematical analysis.

“The essential part of the design of a building consists in conceiving and proportioning its structural system... then, and only then, can we and should we apply the formulas of mathematical theory of elasticity to specify with greater accuracy its resisting elements.”
- Pier Luigi Nervi³

Nervi’s statement further supports the respective roles of each profession, but the absolute necessity of integration needs to occur to produce beautiful works.

However in modern history, especially in the United States, a separation has occurred producing a massive rift between the two professions and this is largely due to the basis of each discipline dealing with the “function” or the “form” first in the design

³ http://shapingstructures.com/gal05_menn.html

sequence. In an effort to become the master builder, the modern engineer pursues functionality first while leaving form secondary, while the architect peruses the opposite.⁴ For the engineer, efficiency and completing the task is essential, while an architect's work is never complete; there is always room for improvement. A similarity can be drawn to the United States military, as there is an "Army Corps of Engineers" but not an "Army Corps of Architects." While this is understandable in the context of war, it certainly is not in the regular day-to-day world; allowing mass production to overrun the built environment is a shame. The engineer has created fantastic pieces of technology in coordination with the architect, but the new developments seem to be an excuse for us not to think. As a result, both disciplines are at fault for letting society lapse into this ideology.

Developmental phases in different parts of the world also contribute to the image of the built environment. The United States was built on the steel industry and to this day, it is still a large portion of our economy. As a result, steel is relatively a cheap commodity in the US and minimally labor intensive. Europe, on the other hand, dealt with masonry for the longest times and forms of concrete as early as the Romans. Due to lower labor costs and lower quantities of steel, many projects, including bridges were concrete. Recent trends show that, in America there is a decline in the use of steel and reinforced concrete, but a huge increase in pre-stressed concrete bridges (figure 1). A chart showing a European bridge inventory would see the same trend of pre-stressed concrete, with a much lower steel bridge percentage and a greater number of reinforced concrete bridges in the earlier days. The trends show that technological advances and strategies to combine steel and concrete have been the major contributing factors. Now

⁴ Corbusier, viii

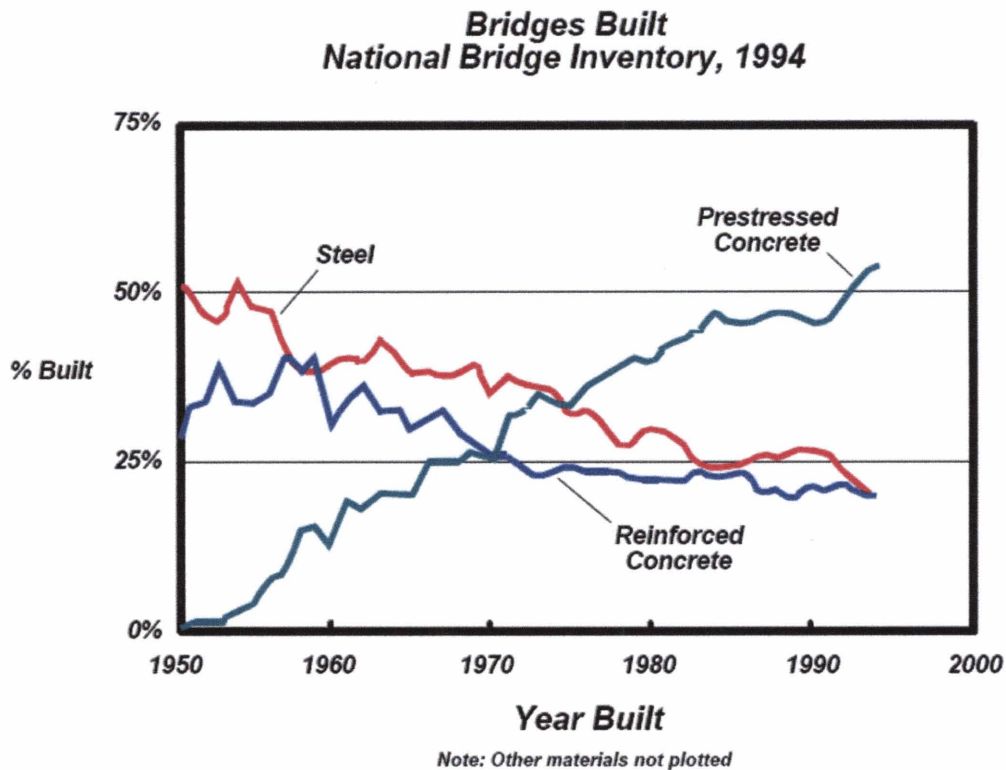


Figure 1 - Percentage of bridge types built in the United States

that the engineering is developed, it is essential for the same technology to produce architecture.

For the bridge, the problem does not get much simpler – connect two points through an obstacle. One would think that an array of ideas to accomplish this would populate the landscape, but this is not the case as seen from the plethora of typical overpasses across the United States. What lacks is attention to each individual site and consideration to what design would best satisfy the given conditions, and that is because the architect was not included in these discussions. The development of infrastructure was largely an engineering job due to the sheer size of the interstate that went underway in the United States in the 1950's. The only way of completing the project without running the nation bankrupt (nevermind its current state) was to mass produce everything including overpasses. Meanwhile in most of Europe, most bridge projects go through a

competition process. Bridges like Norman Foster's Millau Viaduct (figure 2) which traverses an entire 2.5 km valley is a clear example of site, and more importantly architecture, playing an important role in the realization of the bridge. The designers could have just as easily created a rudimentary span in the valley to traverse the Tarn River, but instead tested the limits of cable stay bridges with the current design.⁵ The United States decided on the most efficient method of getting the job done with the most available material, an engineer's method. While the competition method in Europe slowed modernization, their attention to detail and desire for value in the built environment allowed a less brutal movement to evolve. Only the best would be built, and the best does not necessarily mean "the lowest bidder."



Figure 2 – Millau Viaduct

⁵ http://bridgepros.com/projects/Millau_Viaduct/

3 ROBERT MAILLART

Robert Maillart revolutionized the design process of concrete bridges, to breathe life into a topic that remained relatively unchanged for centuries. Before 1900, usually settled masonry arch bridges were used, but if a concrete bridge needed to be built, it was necessary to glorify the concrete; in other words, massive concrete pillars and abutments were typically used as it was believed that more material was always better. Around the turn of the century, a Russian immigrant, Robert Maillart, devised new ideas to achieve new concrete bridge forms. His contributions to the development of the mushroom slab (figure 3), the open three hinged arch, the hollow box arch, and the deck stiffened arch through intuitive analysis versus meticulous computations was a breakthrough in bridge design.⁶ The mushroom slab was developed as a cheap alternative to fireproofing, but



Figure 3 – Mushroom Slab

⁶ http://www.asce.org/history/bio_maillart.html

more importantly allowed for the elimination of beams and joists by making the slab and column essentially one. The tops of the columns flared out and within this flare are rings of reinforcement which increased the support of the above slab.

The development of the hollow-box arch was an effort to create a true monolithic form. Typically, bridges built in masonry by the Roman's had a "disintegrated" form by having loads transfer from the road deck to the perpendicular walls, then to the arches, and eventually the abutments as separate systems. The end result is that the stiffness of the bridge was dependent on the depth of the arch, but by "integrating" the structural systems together, the stiffness becomes contingent to the distance between the arch and the completed deck, substantially decreasing the amount of concrete and increasing the efficiency of the bridge.⁷ This integrated form, desire for exposing the "skeleton", eliminating unnecessary structural members, and creating smooth transitional elements would be a recurring theme in Maillart's work, especially in his bridge designs.

⁷ The Art of Structural Design video

3.1 Tavanasa Bridge – Briel, Switzerland

Prior to the realization of his masterpiece the Salgina Bridge in 1927, Maillart's efforts on the Tavanasa Bridge (figure 4) were primarily centered on the 3-hinged pinned arch. In such a bridge, the entire load channels to the supporting hinge at the abutments and directly above these points, virtually no stresses are present. Tavanasa's goal was to resolve the issue and eliminate the cracks. Two ways to approach this problem is to either reinforce the area heavily to stop the cracks from occurring or completely eliminate the areas of concrete with zero stress, which is what Maillart's solution entailed.⁸ The resulting voids lightened the structure as well as limited the load paths. He used this discovery to push the limits of reinforced concrete in the Salgina Bridge.



Figure 4 – Tavanasa Bridge

⁸ Billington, Reinforced Concrete p. 10.

3.2 Salgina Bridge – Schiers , Switzerland

Since building massive bridge supports in an irregular landscape in the Swiss Alps was burdensome, another alternative was needed to traverse the Salgina span (figure 5). Studying the properties of concrete, Maillart concluded that by making the deck as stiff as possible, the thickness of the bridge arch can be reduced while still taking the load.⁹ His solution prompted the creation of the hollow-box arch. Instead of casting massive supports, the bridge uses the combination of the 3-hinged arch and the deck by connecting the two by a series of reinforced concrete “spandrel” walls in the short span. It takes advantage of the compressive forces acting through the bridge, and concentrates the forces down these spandrel walls and through the narrow arch which are then supported by the abutments creating the “integrated” system. Also, on the periphery of the box beam are slight haunches which eliminate critical sharp corners on the arch,

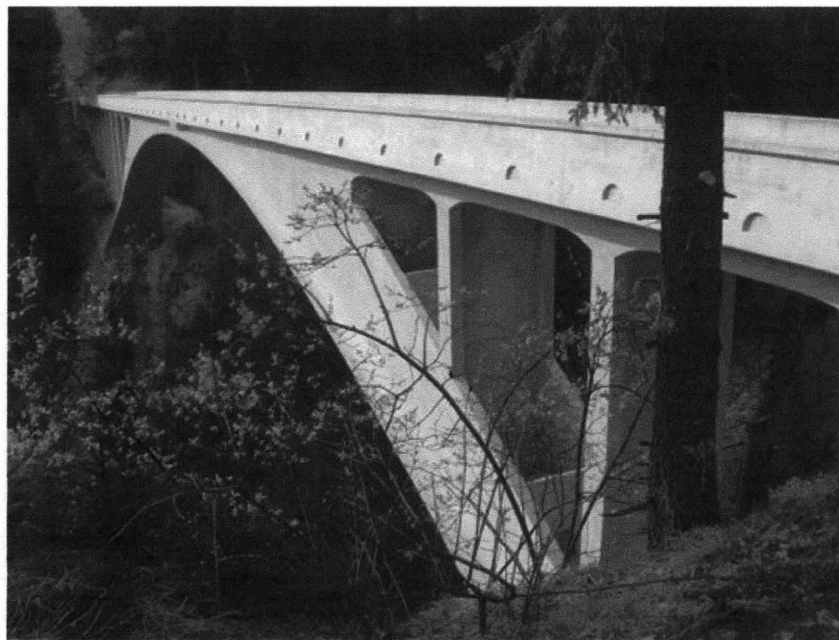


Figure 5 – Salgina Bridge

⁹ http://www.asce.org/history/bio_maillart.html

which could lead to cracking.¹⁰

When observing the completed structure the entire bridge looks to be one piece and is supported by the abutments. However, as stated earlier, this is a 3 hinged arch, and as a result, Maillart was not content since the structure is misrepresented. To accurately portray the bridge, a hinge, or a discontinuity, should be expressed in the center to counter deformity due to temperature, moisture, or seismic changes. Maillart's attention to detail illustrates how, in good architectural taste, he should have displayed how the "form follows function" as the structure in its current state is misleading. He corrects his mistake in his next bridge outside Geneva, by expressing a hinge at the center point (figure 6). Coincidentally, he counters this architectural expression at the same time by making an "engineering" decision. He plays with the spandrel walls sections and arbitrarily shapes the walls in an hourglass form, thus portraying "function follows form."¹¹



Figure 6 – Geneva Bridge

¹⁰ Billington p. 47

¹¹ The Art of Structural Design, video

The deconstruction of the Salgina Bridge by the reduction of concrete allows for a more elegant form to evolve and subsequently, all three attributes of architecture are reached. His discoveries were founded upon observations of previous bridges and a tendency to concentrate on studying the 3-hinged arch which is a determinant structure. Therefore, the computational needs for the bridge forms that would have been conjured by his protégés were unnecessary. Maillart's studies are the preliminary technical answers to designing a modern bridge by demonstrating the question, "what does the (reinforced concrete) bridge want to be"¹² in its pure form. The coming years would heed developments of his ideas by pushing the limits to further maximize concrete's performance and usage.

¹² Webster, p.71

4 OTHMAR AMMANN

Much in the same way Maillart revolutionized concrete, Othmar Ammann glorified and tested steel's capabilities. In the early 1900's, Ammann, among his other work, was the designer for six major steel bridges in the New York City metropolitan area, but none more acclaimed than the George Washington Bridge (figure 7). Many will say that his design decisions were almost always monetarily based and dependent on the national economy. However, the implementation of the newly developed deflection theory in structures nearly three times the size of the typical span at the time is unparalleled. His keen perception of the capabilities of the flourishing building material and his refinement strategies make this bridge worthy of acclaim by Le Corbusier who said, "It is the only seat of grace in the disordered city."¹³



Figure 7 – George Washington Bridge

¹³ <http://www.nycroads.com/crossings/george-washington/>

4.1 George Washington Bridge - New York City, New York

Unfortunately, the final plans for the towers on this bridge called for stone cladding to disguise the intrinsic steel truss design. However, this was not the initial design concept for the bridge as it evolved three times before arriving at its current state. Originally, Ammann designed the towers to be a composite system of steel and concrete, where steel would provide the formwork while the concrete would fill the voids, but in such a system, the concrete would do little to stiffen the towers especially since the concrete would be placed on the outside surface plane of the towers. The concrete was soon deemed to be unnecessary and was far too labor intensive to produce the desired effect. The sudden switch to a masonry façade was considered, but due to the impending depression, it was ruled an extravagant expenditure and stricken from the plans.¹⁴ As a result, what was built was the necessary structure without ornamentation which was widely accepted by the city. What he did not realize at the time was the beauty of the structure he created which visually corresponds to the form of the bridge deck. The composition creates a dialogue between the two parts of the bridge and the engineering becomes the architecture, much like the external façade of the Pompidou Center (figure 8).

¹⁴ Rastorfer, p.43



Figure 8 – Pompidou Center façade

The road decks on the bridge were designed in light of the newly founded deflection theory that proved true for short spans, but Ammann wanted to test the theory on a 3,500 foot length, which at the time more than doubled the length of the bridge that had been successfully tested. The theory states that as the weight per linear foot increases, the need for stiffness decreases since the dead weight of the steel alone would resist movement.¹⁵ Instead of building a complex truss or running guy wires as earlier bridges illustrate, obstructing the views from the bridge, Ammann tried to integrate the system by installing plate girders on the underside of the bridge to accomplish the stiffness requirements. Additionally he designed the bridge to expand to two levels to accommodate the growing population of the city, and once the second level was built underneath, the entire system would work as a box beam (figure 9). Both Ammann and Maillart worked under the same master, Wilhelm Ritter, and it is no mistake that both have received the same tutelage and have applied them to their respective materials. Had

¹⁵ Rastorfer, p.61

Ammann been complacent with convention, the George Washington Bridge would never have been worthy of critical architectural acclaim. Sometimes accidental, but always with good intentions, Ammann's design transformations and structural expression were rooted in the advancement of structural design. The structure became the architecture which was a benchmark for the impending architectural bridge movement.



Figure 9 – George Washington Bridge lower deck

5 CHRISTIAN MENN

Following in the footsteps of Maillart, Christian Menn further developed the form of the concrete bridge. In the late 1950's, Menn started emulating the late Maillart, continuing to remove concrete from the bridge for spans approximately 100m in length. The trend through his bridge designs was drastically reducing the vertical member's sectional dimensions as well as frequency along the span. As seen through the Viamala Bridge (figure 10), the vertical supports between the bed and the arch are nearly invisible



Figure 10 – Viamala Bridge

due to their slenderness and only occur four times through the entire span. It may be hard to discern from the picture, but what has also disappeared through Menn's 1960's designs is the need for a "defined" box beam. Inherently the bridge is still acting as a "deck stiffened arch" in the tradition of Maillart, but with a better understanding of the forces running through the arch, he continued to erode the formwork. However in the 1970's, it was the development of pre-stressed concrete that allowed these ideas to become

reality.¹⁶ The Felsenau Bridge, built in 1974, is the best example to see the transition between the arches and the pre-stressing

5.1 Felsenau Bridge - Bern, Switzerland

The Felsenau Bridge (figure 11) has a main span of 156m which is 1.5 times that of the above mentioned bridges. Deflection theory is not considered here as concrete's properties do not take kindly to these stresses, therefore a different approach was sought after. This increase means that a larger moment must be designed for, and his solution was to cast two hollow box walls that are spaced 12m apart at each support. Typically these walls have been spaced 40 feet apart in the short axis of the bridge, however in the Felsenau design, spacing the column/walls in the long axis helped reduce the moment and also helped in the erection of the hollow box beam construction for the roadway.¹⁷ The

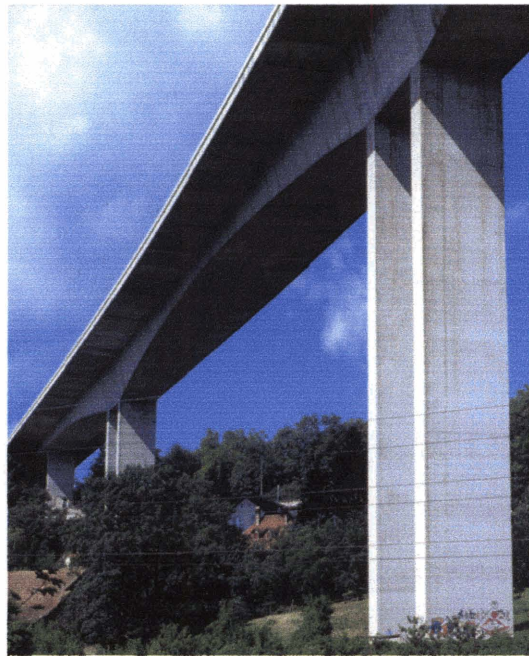


Figure 11 – Felsenau Bridge

¹⁶ http://www.princetonartmuseum.org/Bridges/engineers_7.html

¹⁷ Billington, Civil Engineering

orientation of the supports contributed to opening the view through the bridge to diminish the huge visual barrier.

The arch below the span is significantly flatter than his predecessor's designs. However to incorporate this new technology, revisiting the well defined hollow box concrete girder is essential, as opposed to creating a significantly larger deep girder section. The additional stiffness by using a curved box beam with far less material than it's alternative, a beam of constant depth, lowered the cost of the project. It is true that it takes more intensive labor to achieve such a curved section but overall, the investment was worthwhile.¹⁸

The formwork needed to build the bridge section is limited to each individual cast box section, and then another traveling formwork follows behind to cast the cantilever. Originally, bridges were built with two concrete box sections, but the development of pre-stressed concrete and the desire for cantilevers along the side of the bridge demanded that one larger box section be used (figure 12). Only the top slab is pre-stressed to resist the dead load while the additional non pre-stressed steel resists the live load. The

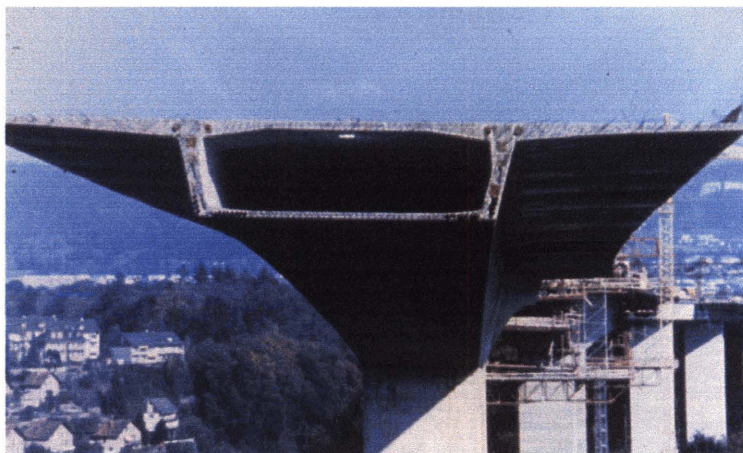


Figure 12 – Felsenau Bridge Section

¹⁸ ibid

dominant load is the concrete, and having the top layer pre-stressed where most of the concrete resides would reduce creep dramatically. A bridge at full live load capacity would have cracking reduced by the additional steel. The result was the largest box girder cross section with a cantilever (26.2m tip to tip) and a substantial reduction of concrete used.¹⁹ Menn's strategy to test the limits of the developing concrete technology is met with architectural praise, as by doing so, the creation of a practical, stable, and beautiful alpine bridge was built.

5.2 Ganter Bridge - Brig, Switzerland

The Ganter Bridge, which followed in 1980, was an improvement on the Felsenau Bridge. There were more stringent restrictions for the support placement on this bridge, and as a result, the spans that needed to be produced were near 175 m long and thus the

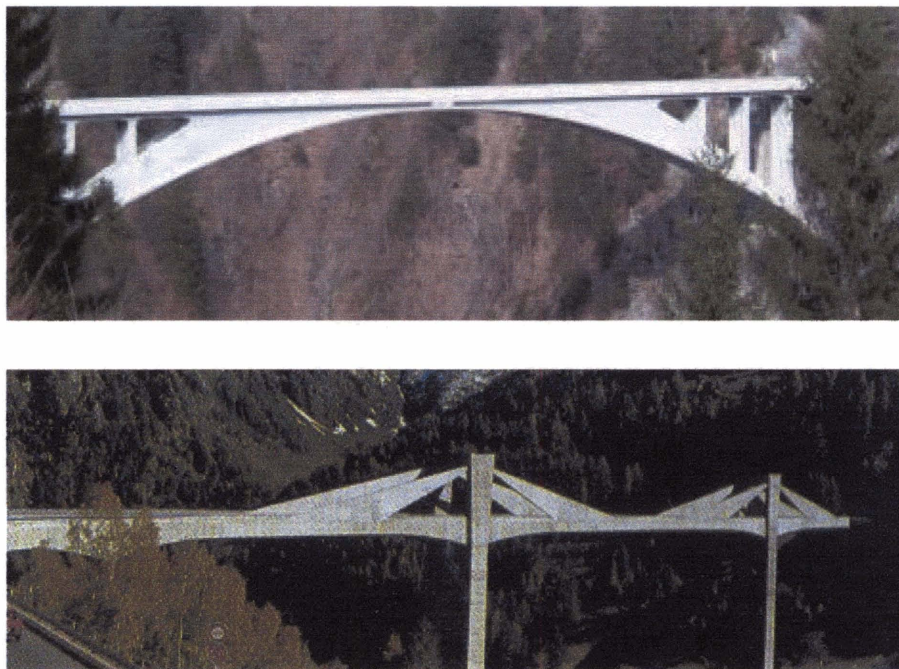


Figure 13 – Maillart's Salgina compared to Menn's Ganter

¹⁹ Menn, p.42

structure needed to be redesigned. In order to minimize the moments at the supports, Menn, instituted a cable stay structure. However, to the casual observer, it looks as if the bridge is being supported by concrete in tension! If one studies Maillart's bridge profile, one can see how he optimized the compression zones located between the roadway and the arch. If the bridge is inverted, then the bridge should work just as well, except the members that were originally in compression are now in tension (figure 13). Through these tension members, Menn reduced the cantilever to a more manageable length, but the use of concrete for tension is still in question. Simply put, the plan of the bridge is curved, and in order for the cables to support the bridge appropriately around the bends, they are cast in concrete, which are the visible walls. Once in position, these walls actually become pre-stressed which eliminates the possibility of cable corrosion as well as eliminating fatigue issues. The underside of the bridge is the same as the Felsenau Bridge, but since it is not as wide, the entire concrete box girder is the width of the bridge. The combination of the pre-stressed concrete walls intersecting the box beam also helps stabilize the span as the cross section is wider.²⁰

Encasing the cables with concrete also gives a sense of proportionality to the observer. It is this balance that gives the bridge its grace; if cables were shown instead, it would have this appearance of immensely tall towers being held together by pieces of insignificant "string" which may make a participant of the bridge uneasy. Therefore by combining aesthetics with developing technology, and adapting to functional issues of concrete, architecture is created. What evolved from these improvements was a new conception of what bridges should look like and it was this view that allowed the next generation of designers freedom to articulate the architectural and engineering dialogue.

²⁰ Billington, Civil Engineering p. 46

6 SANTIAGO CALATRAVA

Since the days of Maillart, Ammann, and Menn, no one has revolutionized the way society looks at bridges like Santiago Calatrava. From his early days working on alpine bridges fresh out of engineering school, one could say that he picked up exactly where Menn left off. In these few alpine design proposals, he uses traditional pillar supports, however, the reinforced concrete is at a minimum due to the concrete box girder. A skeletal, bare-bone, appearance is sought after, minimizing structural elements and in essence mimicking the figure of the human body.²¹ Even though the bridge is not at the size of a human, relating the proportions of the human body to a structure can communicate scale to the observer. Much like Maillart, Calatrava's intuition guided his design, but the capabilities of the reinforced concrete always governed the final result. Unlike other architects who design in plan or section, Calatrava designs for moment, and unlike engineers, he pushes the envelope to make his structures atypical. The following tracks the design process of his masterful bridges which optimize the use of reinforced concrete to make Vitruvian architecture and what Corbusier calls "The Engineer's Aesthetic" and "Architecture" which should march together hand in hand.²²

²¹ Tzonis, *The Bridges*, p. 33

²² Le Corbusier. p. 13

6.1 Acleta Alpine Motor Bridge – Disentis, Switzerland

To complete his studies at the ETH in Zurich, Calatrava designed a bridge that eerily resembles the work of Maillart and Menn, however the reason for designing these bridges comes from different inspiration. Studying the combination of the arch bridge and the cantilever, he wanted to devise a system to separate the three forces of tension, compression, and bending moment at the support. Hence the reason for the eroded support that Calatrava envisioned as a human body holding up the road (figure 14).²³

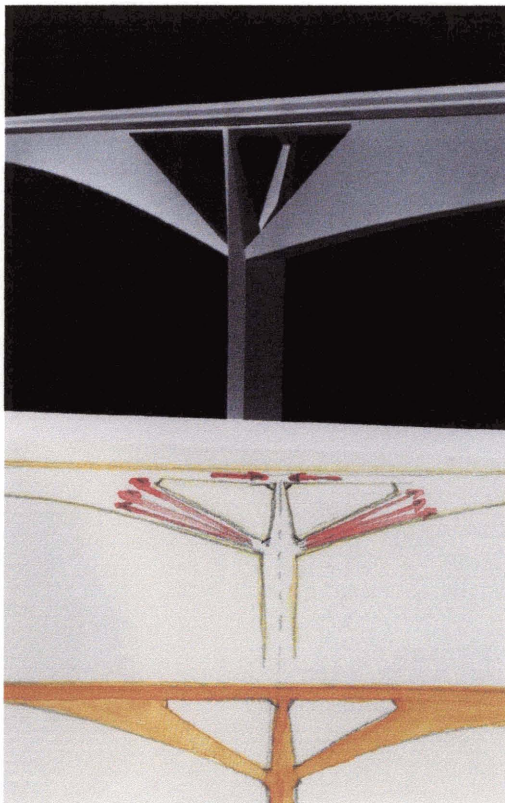


Figure 14 – Acleta Option 1

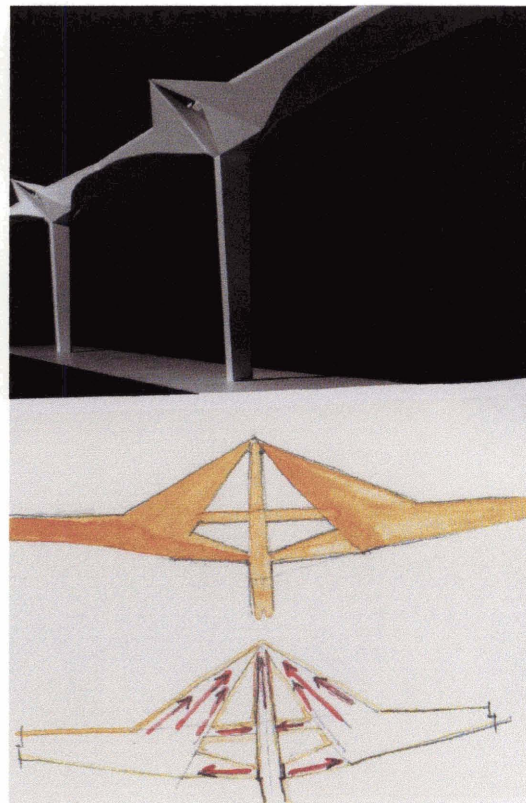


Figure 15 – Acleta Option 2

Through iterations, Calatrava formed different ways to remove redundant elements in the form for this bridge. From the outstretched “arms” holding the deck to extending the pylon above the deck and transferring tension through cables being cast

²³ Calatrava, Conversations, p.55

through a concrete deck (figure 15); this option is very similar to Menn's Ganter Bridge concept, but Calatrava's reason for attempting this is different than, "the cables need to follow the bridge deck around the curves." Instead, Calatrava envisioned that, it would reduce the thickness of the lateral walls of the pylons and transmit shear forces more efficiently.²⁴ These changes were Calatrava's way of playing with the concept of the free cantilever at the support. Knowing that, another alteration made was tapering the bottom portion of the roadway to differentiate between the top and the bottom of the bridge section, despite the fact that it is in compression and an obvious contradiction to logic.²⁵ Eventually Calatrava opted for the first iteration, but what is important in all these options is the variety. These decisions were based not just on one aspect but a combination thereof. The exploration of forms provides limitless opportunity to think "outside the box." Site, material, structural behavior, and architectural forms were conceived and altered to push the limits of technology. New conventions and their practicality were tested, and through careful analysis, a merit based solution was chosen, rather than simply defaulting to the original idea.

²⁴ Tzonis, *The Bridges*, p. 39

²⁵ Calatrava, *Conversations*, p.55

6.2 Alamillo Bridge – Seville, Spain

Built to be the iconic structure of the 1992 World Expo, the Alamillo Bridge extends over the Guadalquivir River in one 200 foot span and utilizes one pylon extending 142 feet in the air to support the entire structure via cable stays (figure 16). The pylon, which is hollowed out to provide service along the height, has a steel core and is then filled and formed with reinforced concrete. The 13 steel cables that come off the pylon are attached to the central span of the bridge which is a hexagonal steel box beam with cantilevered supports on either side for the roadways. The most amazing thing about the structure is that it has no counter-stays to help support the leaning tower which produces huge stresses and moments at the base of the column.²⁶

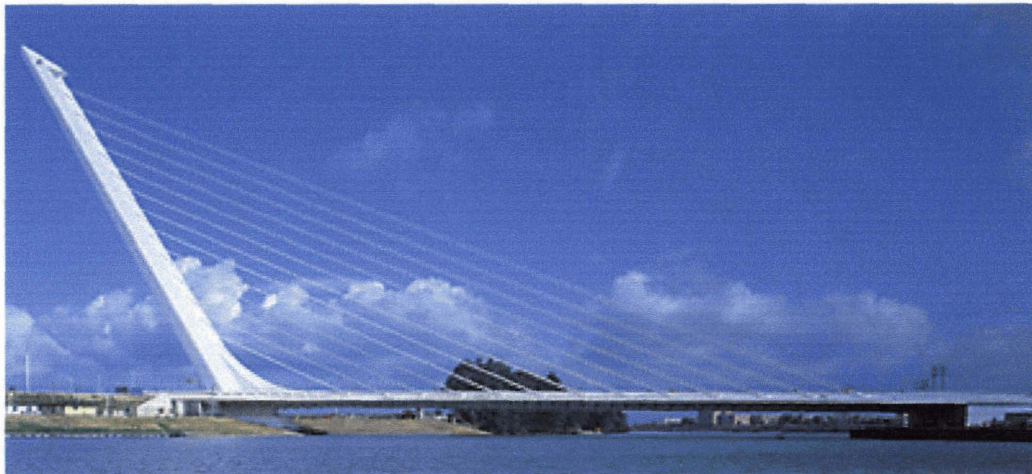


Figure 16 – Alamillo Bridge

²⁶ Tzonis, *The Bridges*, p.98

The original idea for the Alamillo Bridge (figure 17) was to have two of the above mentioned pylons on either side of the river leaning away from each other as the road intersects the same river twice, but due to budgetary constraints only one pylon was

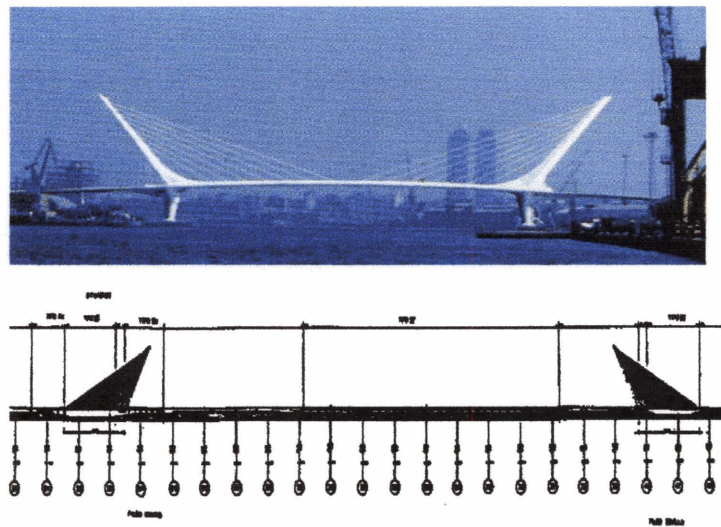


Figure 17 - Diagrams comparing Calatrava's proposals of the Alamillo bridge (top) and Port de Barcelona (bottom).

sought after. However, one must consider Calatrava's thought process. In the development of the project, the ever present tutelage of Maillart and Menn (who graduated from the ETH prior to Calatrava's tenure) expressed itself in the project similar to the Ganter Bridge. In the proposals of this bridge, the comparisons are scant, as the bridge is inverted and mirrored, but later in his career when he proposed the Port of Barcelona project, it is obvious the relationship between the compression and tension arch (figure 15). Menn used this technique in his Ganter Bridge described above, but never fully expressed the capabilities. Tension members can be smaller than compression members, and since concrete is worse in tension than compression, Calatrava thought the outright expression of steel cables was needed to fully grasp the

fundamentals of the bridge. The forces exhibited in this bridge design could not have been easily realized had it not been for the studies of his concrete bridge ancestors.



Figure 18 - Alamillo bridge support

Another point about the way Calatrava uses concrete is the way the joints are pronounced on the structure. The pylon narrows at the top and then gradually widens as it grabs the wires along the length and elegantly splays as it meets the ground (figure 18). The gesture Calatrava is trying to communicate is of plasticity and continuity since the transition between pylon and the ground is an integrally cast moment connection.²⁷ The monolithic approach simplifies the transfer of forces, and allows the structure to be stable. The tilt of the composite pylon does not make the bridge unstable, but in fact is at such an angle that the dead weight acts as the backstays that would be exhibited in any other like structure. This behavior is similar to how masonry towers in Gothic construction countered thrust given off by flying buttresses.²⁸ Overall, concrete

²⁷ Webster, p.70

²⁸ Webster, p.69

displayed in this fashion helps dictate its behavior much easier, and without it, there is some skepticism as to whether a pure steel column of that profile could do the same.

6.3 Sundial Bridge – Redding, California

At first glance, this 722' span (figure 19), used to link an arboretum to an ecological museum, is the typical Calatrava bridge. It embodies the classic massive leaning pylon and cable stayed structure, however, particular attention was paid to the environment the bridge would serve. The entire bridge span is made up of hollow structural steel truss framework that does not interrupt the flow of the river which is a breeding ground for the salmon population. The bridge deck is constituted with glass along the span in between slender steel holders so that even shadows do not play a part in the river habitat.²⁹

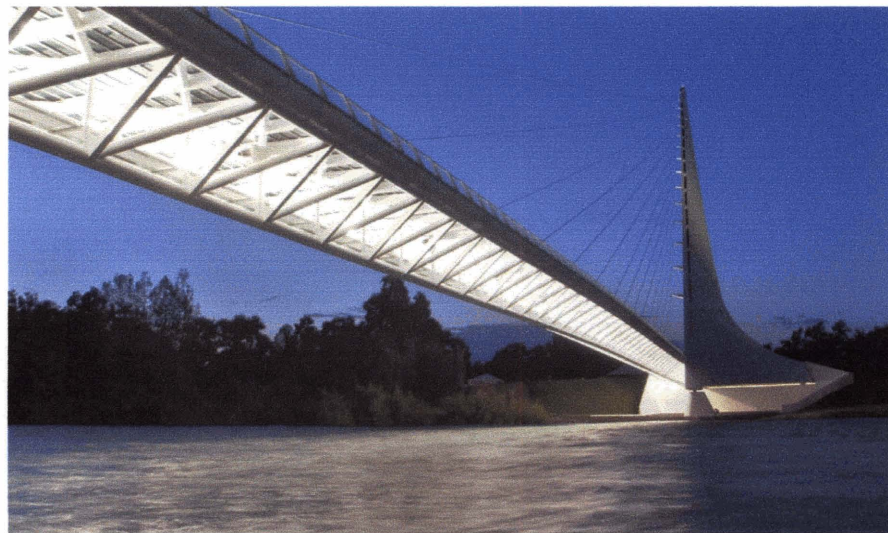


Figure 19 – Sundial Bridge

²⁹ Tzonis, The Bridges, p. 150

The bridge's relative lightweight structure helps in the overall construction process; while there is a substantial moment at the base of the pylon as with any one of Calatrava's similar bridges, the lightweight decking (figure 20) allows the pylon to be made of less massive material. Instead of having a composite concrete and steel structure running the entire length of the pylon, he uses a double steel wall pylon, gradually decreasing the thickness as the structure heads skywards. The pylon supports the bridge via 14 cable-stays and its North-South orientation and 36 degree slant make it a gnomon for a sundial.³⁰ Additionally, the interior of the pylon as mentioned above is hollow, but can be accessed by pedestrians to form a view of the sky, essentially linking this natural park to the heavens.

The construction phases for this project were not easily realized as this was the architect's vision and it was up to the engineers to make it work. Intense 3-D modeling, including determining the irregularly shaped curved surfaces at the base of the pylon and

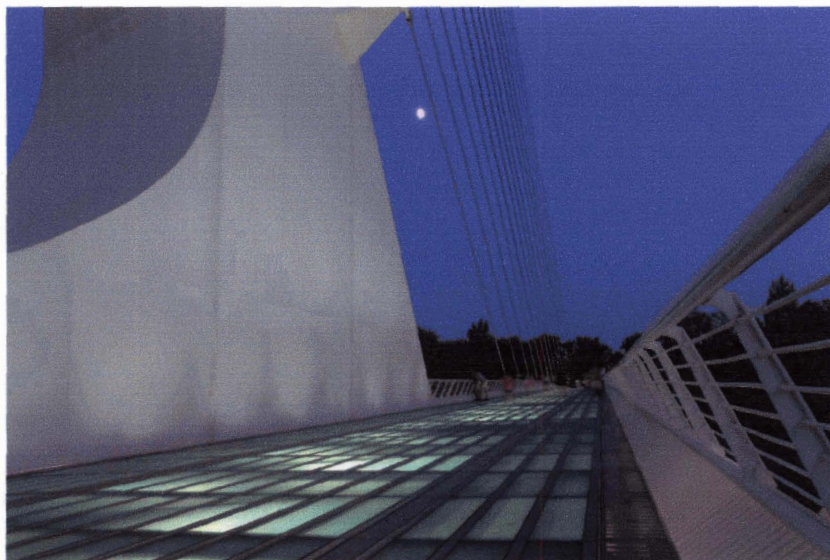


Figure 20 – Sundial Bridge Decking

³⁰ Menlick, p.26

cambering techniques for the asymmetrically proportioned bridge, was needed to accomplish the project. They could have just as easily placed a typical span between the two points, but the project's demanding requirements forced architect and engineer to think beyond what was already commonplace. Everything was custom designed, which is a huge burden on the fabricators, but without these new techniques the bridge would have been unattainable. Also, linking the bridge at the microscale (the park) and macroscale (the heavens/universe) played an implicit part to the success of the project, making this not a “cookie-cutter” bridge that can be placed anywhere. Heightened awareness about size, scale, time, and individuality are communicated giving a more enriching experience than the typical highway bridge. The form of the bridge exactly represents the function desired, which is credited to technological advances in materials.

6.4 Bach De Roda Bridge – Barcelona, Spain **9 d'Octubre Bridge – Valencia, Spain**

The way concrete was employed in the Bach De Roda Bridge and the 9'de Octubre Bridge is quite different than the aforementioned, however both methods aim at



Figure 21 – Bach De Roda Bridge

the same concept, the illusion of a lightweight structure. In the double arch system, used to prevent buckling in the Back de Roda design (figure 21), steel and concrete are used compositely to give the structure a firm base rooted into the ground. Out of the foundation, the steel arches extend out of the reinforced concrete abutments creating a form suggesting movement.³¹

In the 9'de Octubre Bridge the opposite is observed in the form. Immediately the numerous concrete abutments are noticed and then the concrete bed extends out beyond these abutments along slender steel pylons positioned behind (figure 22). The actual



Figure 22 – 9'de Octubre Bridge

sizes of these concrete abutments are miniscule compared to the enormous concrete deck placed on top. The use of post-tensioned cables in the 2 foot reinforced slab allows for structural stability and through that mechanism, the appearance of a suspended lightweight structure is achieved.³² Calatrava also uses a modified mushroom slab technique with the concrete column creating a capital that can take more of the immense dead load. While Calatrava uses both bridges to exhibit opposite first impressions, his

³¹ Webster, p.72

³² Frampton, Calatrava bridges, p.37

intent of using concrete to achieve the desired architectural form and push concrete's capabilities is successful.

6.5 Milwaukee Art Museum Pedestrian Bridge – Milwaukee, Wisconsin

While the intriguing and glorified feature of this building is the winged movable steel sunscreen, the design and construction of the adjacent pedestrian bridge is equally fascinating. Upon first inspection, this is one of his few cable-stayed bridges that has a wired backstay, and the reason for that is the steel pylon is not capable of holding the entire span of the bridge (figure 23). The museum can not be dwarfed by a massive bridge support, and Calatrava tries to blend the slender steel pylon in with the museum by angling it parallel to the building spine. Instead of placing the concrete on the pylon, or making an extended steel section of pylon, he sinks the anchoring concrete in the ground and introduces the backstays. The tensile structure continues to reinforce the image of a



Figure 23 – Milwaukee Art Museum Pedestrian Bridge pylon

lightweight, almost flying structure, which would otherwise be ruined by a visible monstrous concrete base. Disguising the weight is a key element to making all parts of the museum work together; an architectural requirement satisfied by engineering practice.

The other factor to make this bridge work as intended was to create a lightweight bridge system that the pylon can hold. As it is, the pylon needed to be skinny so any unnecessary weight and forces acting on the pylon needed to be eliminated. The solution was to develop a pentagonal steel box beam inherently making a stress-skin structure with no internal beams or girders for additional support. It is the walls of the 2ft deep by roughly 17ft wide section that resists stresses from the elements.³³ The lightness of resulting hollow bridge section allows the entire system to work and reach the programs architectural goals.

³³ Badreddine, p. 43

7 CONCLUSIONS

The evolution of bridge building can be evaluated in one simple term – construction. “Construction embodies material and its use according to its properties”³⁴ says the Greek architect Aris Konstantinidis, and with good reason. The development of steel and reinforced concrete was a venture to exploit the value of the material while glorifying the unique method of construction.

Maillart saw potential in the alternative to masonry and as a result created forms that were not standard. His intuitive knowledge of concrete allowed him to create a form that represented the behavior and in order to create this form, the construction process was relatively simple. As a structural engineer, Maillart can be argued to have applied “function follows form,” as is the stereotypical nomenclature of an engineer, but as a self proclaimed structural artist and his attention to the construction process of forms classify him as much more than just an engineer. Nearly all of the developments in his designs were made to improve the forces acting through the bridge. Therefore, as Corbusian doctrine states, he let the form follow the function in true architectural spirit.

It is also noteworthy to mention that Maillart’s bridge forms, especially Tavanasa, were only appreciated by the public later in his life.³⁵ Rudimentary engineering usually repeats well known, easily manufacturable forms that are respected in the community, but only the most daring engineers and architects fight convention. It was only through years of criticism that the true practicality, beauty, and stability were accepted and an architectural form is recognized.

³⁴ Frampton, *Studies in Tectonic Culture* p.335

³⁵ *The Art of Structural Design*, video

Ammann's development process was a bit more accidental, but what he failed to realize during the initial phases of the George Washington Bridge was that steel can be a brutal material but treated in an elegant manner. Ammann had succeeded in acquiring elegance, but was going to cover up the masterpiece. Less is more! Revealing the structure of the towers and the rest of the bridge can be considered the first attempt, on a large scale, to show how typical bridge engineering can become architecture. This opened the door to future projects, to push the limits of materials and demonstrating them in an unabashed fashion.

Menn's refinement and experimentation with Maillart's ideas by pushing the limits of the hollow box beam and pre-stressed concrete started the shift of appreciation of these forms. The Ganter Bridge form starts to pose the question of how else can concrete be used while still complying with natural load paths? Better technology would help increase these possibilities

By the time Calatrava started designing, the boundary between architecture and engineering became indiscernible. Due to the developments of Maillart, Ammann, and Menn, Calatrava allowed his creative license to combine with his engineering education making bridges that incorporate the tools from both professions. This iterative development process of steel and reinforced concrete illustrates how bridge design has evolved into "arch-ineering"³⁶ as coined by Werner Sobek and Helmut Jahn, which is something greater than what the engineer or the architect can obtain alone; as a synthesized team, this concept is not far from reach.

³⁶ Sobek lecture, Harvard GSD

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